

**DELAY/DOPPLER RADAR ALTIMETER IN LITTORAL REGIONS**

R. Keith Raney

Johns Hopkins University  
Applied Physics LaboratoryJohns Hopkins Road  
Laurel, MD 20723-6099

phone: (301) 953-5384, fax: (301) 953-5548, e-mail: keith.raney@jhuapl.edu

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**LONG-TERM GOAL**

Recent discovery of the delay/Doppler technique (Raney, 1996) opens new opportunities for radar altimetry. This new technique promises relatively fine spatial resolution, greater precision, substantially improved tracking and measurement accuracy near coastlines and surface feature contrasts, and reduced on-board power requirements. These attributes should translate into better performance from a smaller, less expensive instrument, a prediction that as of now is untested. The main thrust of this and related projects is to respond to that challenge: demonstrate that the delay/Doppler altimeter is a compelling candidate for an advanced instrument that would meet the requirements of future satellite radar altimeter missions.

**SCIENTIFIC OBJECTIVES**

Effective use of altimetry in the littoral region depends on two general factors: the instrument's capabilities, and the environment's characteristics. The two main objectives of this project are: to generate a more realistic prediction of the performance to be expected from a delay/Doppler altimeter, particularly in the near-shore regime; and, to assess the utility of (radar) altimeter data in a littoral information system.

**APPROACH**

Three primary Tasks have been completed that address these two objectives, and a specialists' workshop was convened. Task 1 looked at the instrument itself, especially the tracking and precision issues raised by the unique delay/Doppler waveform, which is much sharper than that of a conventional radar altimeter. The primary tool employed was computer simulation (J. R. Jensen). Tasks 2 and 3 looked at wind speed (WS) and significant wave height (SWH) measurements in the near-shore region, and at the correction techniques required to extract the height signal, an especially challenging problem in the near-shore environment (E. B. Dobson, F. M. Monaldo). As a part of these tasks, a workshop to address the utility of radar altimeter observations in coastal regions was held at JHU/APL on 14-15 May 1997. The invited participants included representatives from the oceanographic research community and Navy operational oceanography commands, as well as altimeter instrumentation and data application investigators.

Coastal Altimetry Utility Workshop Participants include: Dr. Frank Aikman, Dr. John M. Bane, Dr. John P. Blaha, Dr. Marie Colton, Dr. Richard L. Crout, Mrs. Ella B. Dobson, Dr. Richard F. Gasparovic, Dr. Scott M. Glenn, Mr. Ray Godin, Dr. Paul A. Hwang, Mr. Gregg A. Jacobs, Dr. J.

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Robert Jensen, Prof. Lakshmi H. Kantha, Mr. Charles Luther, Mr. Frank M. Monaldo, Dr. David L. Porter, Dr. R. Keith Raney, Prof. Allan Robinson, Dr. Colin Y. Shen, and Dr. C. K. Shum.

## WORK COMPLETED

The predicted performance of a delay/Doppler radar altimeter has been evaluated based on computer simulations that compared it to a similar conventional radar altimeter, both modeled as operating over the ocean surface. The simulations were based on the generation of random altimeter waveforms from mean waveforms, including additive noise and speckle. These waveforms were noncoherently integrated to compute averaged waveforms that were then subjected to the gate tracking algorithms to extract the geophysical parameters.

For this study, performance was assessed through the relative precision with which the range (indicating surface height), the coefficient of surface reflectivity  $\sigma_0$  (hence, by inference, surface wind speed), and the significant wave height parameters could be determined from the data generated by the simulations. For the delay/Doppler altimeter, these three parameters were extracted from the waveforms with the use of a set of new and unique tracking gates (derived under this project). For the conventional altimeter, parameters were estimated in standard fashion, as is done on TOPEX, for example.

Coastal regions are strongly influenced by the local meteorology, bathymetry, and oceanography, and are characterized by large variability over small space and time scales. These influences impose larger and more abrupt contrasts on the oceanic surface features, steeper gradients in the atmospheric characteristics that affect radar pulse propagation time, and new static and dynamic conditions that impact the attempt to extract a geophysical signal from the altimetric height record. Factors considered by this project, and explicitly examined by the coastal altimetry workshop participants, included:

1. Sampling limitations: altimeter footprint, ground track spacing, orbit cycle and revisit time;
2. Spatial (xy) and temporal (t) sampling gains from multiple altimeters;
3. Measurement limitations (instrument-specific) near land boundaries;
4. Accuracy of existing WS and SWH algorithms in coastal areas;
5. Utility of WS and SWH observations for assimilation into wind/wave forecast models;
6. Tide, geoid and orbit precision requirements for coastal applications;
7. Use of altimeter observations to improve coastal tide models;
8. Magnitudes and scales (xy, t) of height signatures of coastal circulation features;
9. Value added from assimilating altimeter observations in coastal forecast models;
10. Special validation requirements for geophysical algorithms; and
11. Implications of scales (xy, t) of coastal phenomena on traditional methods for deriving height corrections from water vapor, E-M bias, and ionospheric effects.

## RESULTS

Unique weighted tracking gates were derived that are matched to the delay/Doppler waveform (Jensen, 1997). A major advantage of these gates is that they produce values that can be converted to geophysical measurements (H, WS, and SWH) through the same models and algorithms that have been developed for conventional radar altimeters, thus capitalizing on an extensive heritage. The theory is generalizable to any non-symmetric waveform, including biases introduced by antenna pattern weighting or mis-pointing.

Based on the waveform simulations and subsequent application of the appropriate gates, the performance to be expected has been calculated. Results for 1-second averages are shown in Figure 1. For each type of altimeter two cases are included, corresponding to no thermal noise, and a signal-to-noise ratio of 10 dB. The results show that the precision of the delay/Doppler radar altimeter exceeds that of a conventional altimeter for all three geophysical measurements, by as much as a factor of two or more.

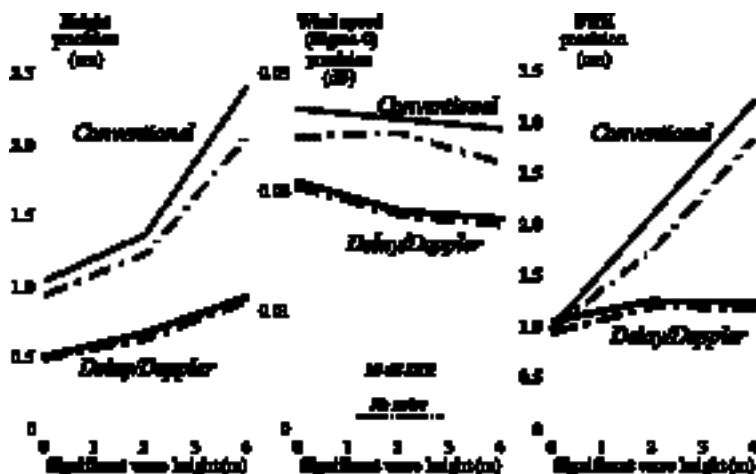


Figure 1. Comparative measurement precision derived from computer simulations of a delay/Doppler radar altimeter and a conventional radar altimeter.

The performance advantage of the delay/Doppler altimeter is a consequence of its sharper waveform and the larger amount of noncoherent averaging available. This latter claim may seem counter-intuitive: usually finer resolution and increased averaging are mutually exclusive trade-offs in signal processing. In the case of the delay/Doppler altimeter, however, the Doppler signal decomposition coupled with delay compensation captures much more of the received signal to be converted into the surface response waveform. In effect, the delay/Doppler algorithm converts signal energy that would otherwise be wasted into useful energy, hence the performance gain.

Simulations show also that the delay/Doppler measurements at the highest resolution (250 m along-track) are as good as or better than the highest resolution measurements from a conventional radar altimeter (~3 km along-track) in spite of the finer (along-track) footprint size. This result reinforces the expected applicability of delay/Doppler radar altimeter measurements to the sharper and larger contrasts found in the littoral zone.

Judging by the views of the workshop participants (Gasparovic, et al., 1997) and our studies of the impact of the littoral environment on altimetric measurements, there is general consensus that

coastal altimeter observations can contribute valuable information for a variety of applications. WS and SWH parameter estimation present fewer difficulties and challenges to be overcome to generate products, than height measurements that require corrections which usually are an integral part of the product-generation process.

There is evidence that the accuracies of coastal wind and wave estimates derived from existing deep-water algorithms are comparable with those obtained from deep-water observations. The spatial resolution of conventional altimeters frequently incurs loss of fine-scale tracking near land boundaries however, precluding observations closer than 20 km from shore. This limitation could be reduced by more than an order of magnitude with a delay-Doppler altimeter. (Of course, development of a new method for waveform retracking might allow use of conventional data somewhat closer to land, but so far there has been little progress.) The workshop participants recommended a focused and more extensive effort to compare altimeter wind and wave data rigorously with buoy observations in coastal regions, paying particular attention to grouping the observations according to atmospheric stability and other systematic environmental conditions.

Extracting height signals requires precise and accurate height measurement as well as analysis techniques and models that relate height variations to physical processes. While highly refined techniques have been developed for correcting altimeter range measurements to extract surface height signals in deep-ocean areas, coastal observations can impose more demanding requirements. For example, conventional microwave radiometer measurements cannot resolve the small-scale horizontal gradients in water vapor accompanying coastal atmospheric events. At present, knowledge of geoid variations at small spatial scales is inadequate for accurate corrections and better information is needed on gravity and tide-induced long period errors affecting precision orbit determination. Improvements in coastal tide models are needed for accurate tide corrections. An important issue to resolve is whether altimeter data can be used to significantly improve coastal tide models, perhaps emulating the success achieved with refining global tide models.

The transformation of surface height signals into ocean current information is straightforward when geostrophic balance applies. Coastal jets and buoyancy fronts, shelf eddies, and boundary currents are probably in quasi-geostrophic balance, but other components of the general flow field will produce height signatures which do not map directly to currents. Interpretation of this class of signals will require assimilation of altimeter data with other observations in numerical models for the oceanographic fields. While acknowledging the challenge presented by the latter situation, there was a strong endorsement from the participants for developing methodologies to incorporate altimeter observations as an integral part of coastal dynamics investigations.

Finally, recognizing that daily observations from three satellite altimeters (TOPEX, ERS-2 and Geosat Follow-On) will soon be available, there is a need also to quantify the value added from combining altimeter data from multiple sensors having asynchronous spatial and temporal sampling. It was noted that for some naval applications, a long endurance remotely piloted aircraft equipped with a radar altimeter would afford dense space-time sampling of a coastal area of interest, providing a very effective way to supplement satellite observations.

**IMPACT/APPLICATION**

The delay/Doppler altimeter is acknowledged to be the paradigm of a new generation of radar altimeters. It is under consideration by NASA/JPL as an experimental payload for the Jason-2 mission (should that ever materialize). It is potentially the only satellite altimeter technique that is both unimpaired by clouds and able to cope with the (small) surface slopes encountered on the earth's continental ice sheets. It shows promise for either remotely piloted aircraft or satellite implementation for the Navy in support of a coastal ocean information system.

**TRANSITIONS**

An aircraft version (partial) of a delay/Doppler radar altimeter (augmented with the phase-monopulse feature that offers cross-track angle discrimination) is being implemented by JHU/APL in support of studies for NPOESS (see following paragraph). Satellite versions are under study in U. S. industry (Raytheon E-Systems) and abroad (Surrey, UK; Alcatel Espace, France).

**RELATED PROJECTS**

JHU/APL is studying the utility of an advanced radar altimeter on the converged polar-orbiting environmental satellite system now in the planning stage for operational deployment in 2008 (Raney, et al., 1997). The principal tasks of that study are: (1) mission analysis (orbit selection trade-offs within the NPOESS constraints), (2) performance analysis (expected altimeter measurement precision as a function of ancillary measurements and orbit determination); and (3) AAPHE-2 (Advanced AAFE Phase Experiment). The latter task is devoted to modification and extrapolation of the Advanced Applications Flight Experiment (AAFE) altimeter to an advanced two-channel version that will be flown in an aircraft to record complete signal files. These data will be processed (later, in the laboratory) according to the Delay/Doppler phase-monopulse algorithm. (Funding for the flight portion of the program has not yet been identified.)

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